Stabilized Liner Compressor (SLC) for Low-Cost Fusion Development

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ALPHA Program for Development of
Low-Cost Controlled Fusion Power

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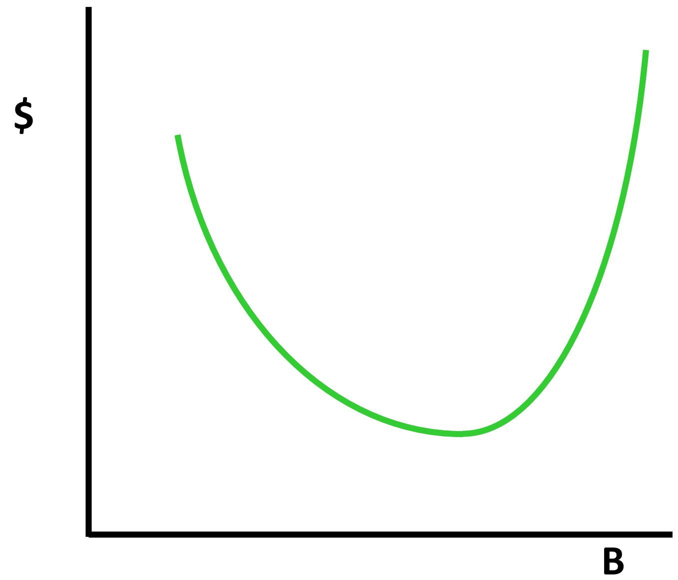
In late 60's, Russians recognized that megagauss magnetic fields could reduce the size and cost of fusion experiments, inspiring the Linus program at NRL.

System cost: $\$ = C_w W_p + C_p P = C_w W_p + C_p'/W_p^{3/2}$

Magnetic Confinement

MCF

Strong adiabatic compression to megagauss fields provides fusion temperatures without costly beam- and RF-heating systems.



P.J. Turchi, "Issues of Liner-Plasma Compression," 2006 International Conference on Megagauss Magnetic Field Generation and Related Topics, Santa Fe, NM, Nov 2006. Also, P.J. Turchi, *IEEE Trans. on Plasma Science*, 36, 1, 52 (2008).

Inertial Confinement

ICF

Inclusion of magnetic fields reduces thermal loss and retains alpha particles, lowering power density for ignition and high gain.

MCF and ICF communities approach MTF/MIF with different emphases: efficient adiabatic compression vs ignition and issues: Rayleigh-Taylor instability vs "kopek" problem.

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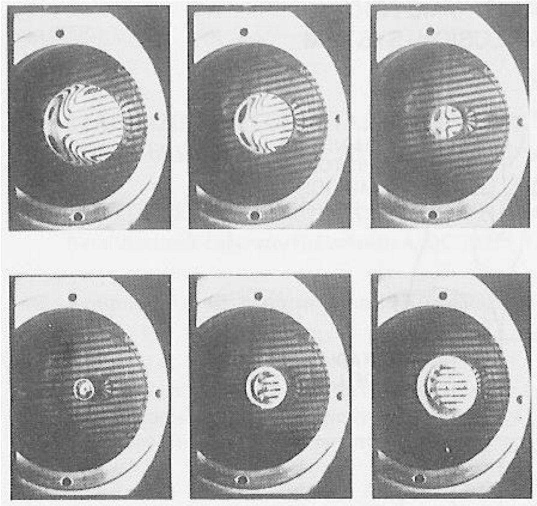
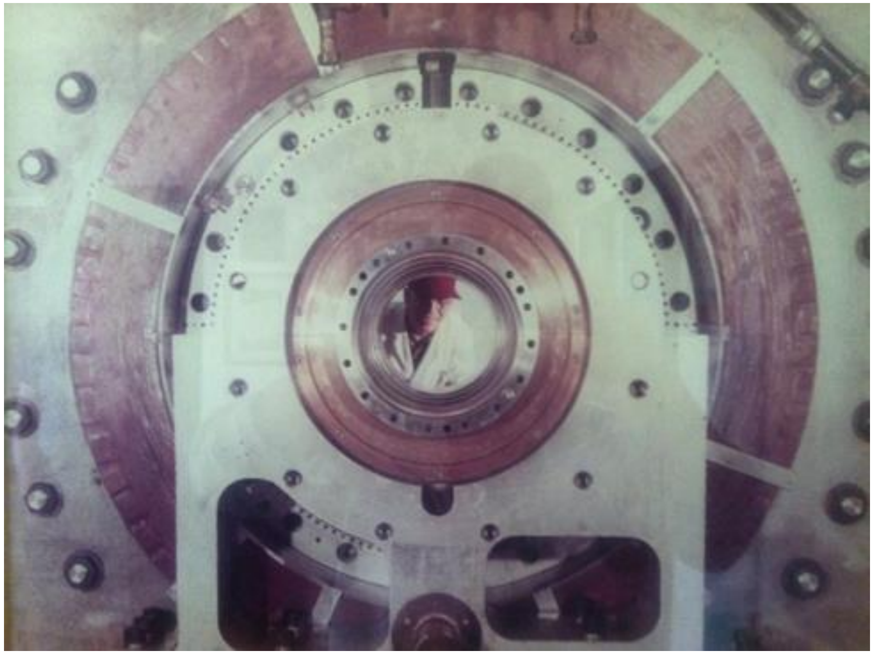
The Stabilized Liner Compressor concept builds on technology from the NRL Linus program, c. 1977-1979.

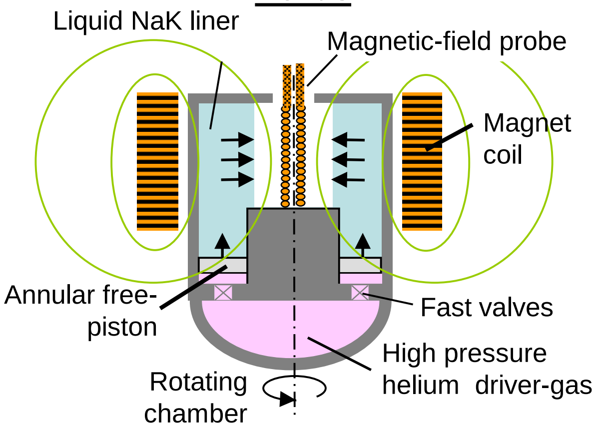
"Water Model"



Linus-0



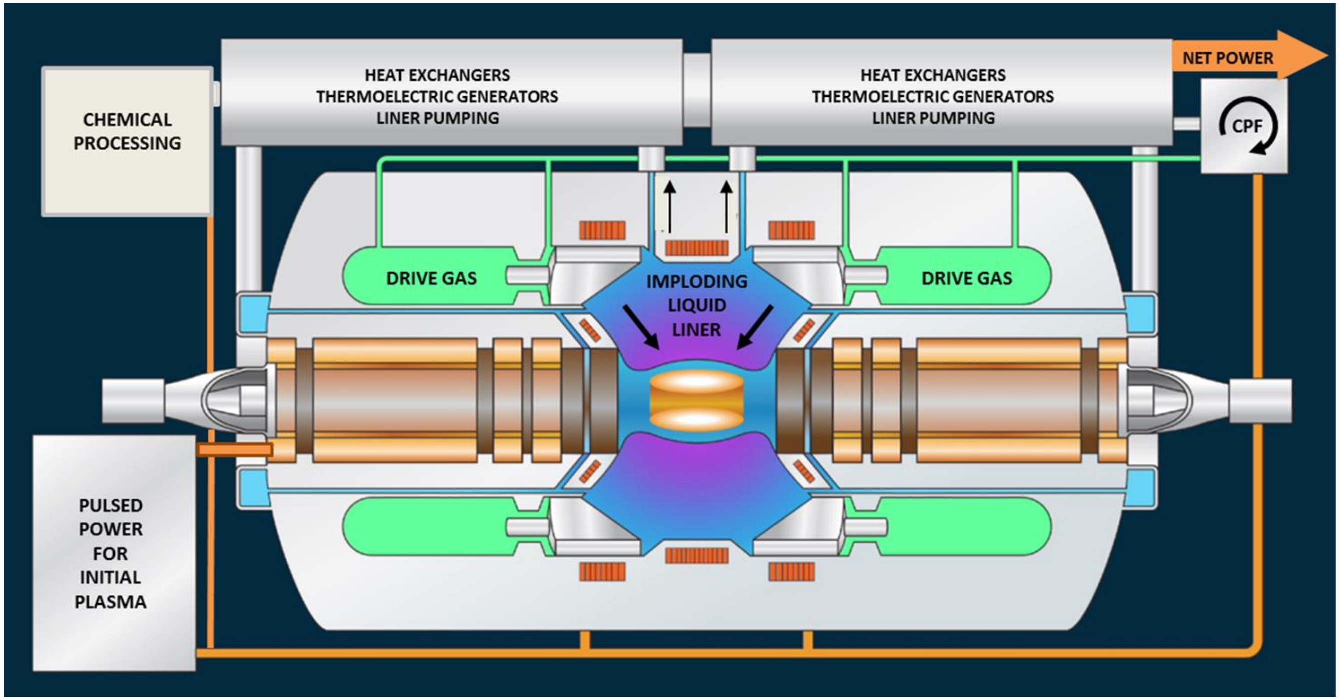
Helius



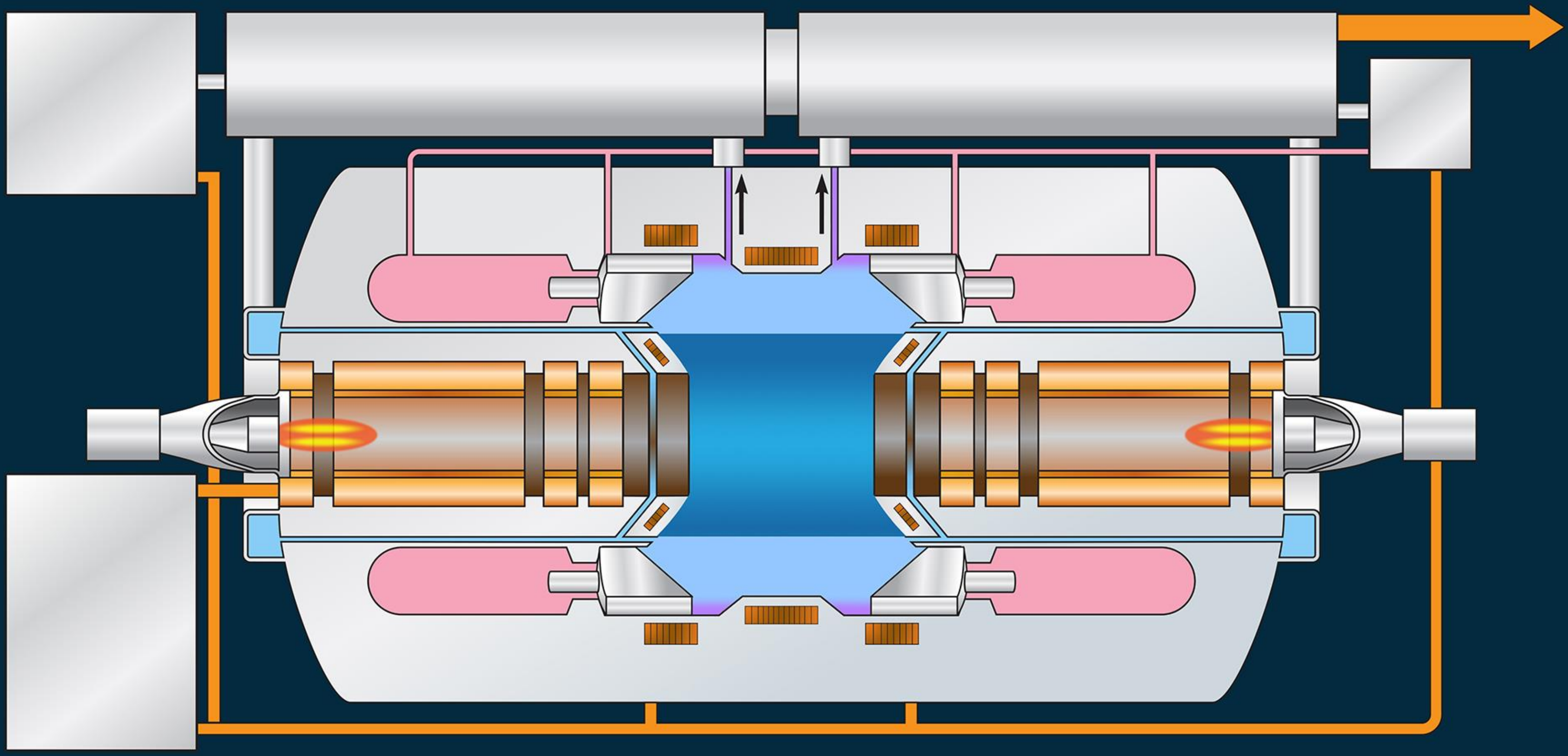
P.J. Turchi , et al, "Review of the NRL Liner Implosion Program," in Megagauss Physics and Technology, ed. P.J.Turchi (Plenum, 1980). P. 375.

With an eye toward break-even experiments and the power reactor, techniques were developed for repetitive implosion and re-capture of the liquid liner, based on rotational stabilization and free-piston drive.

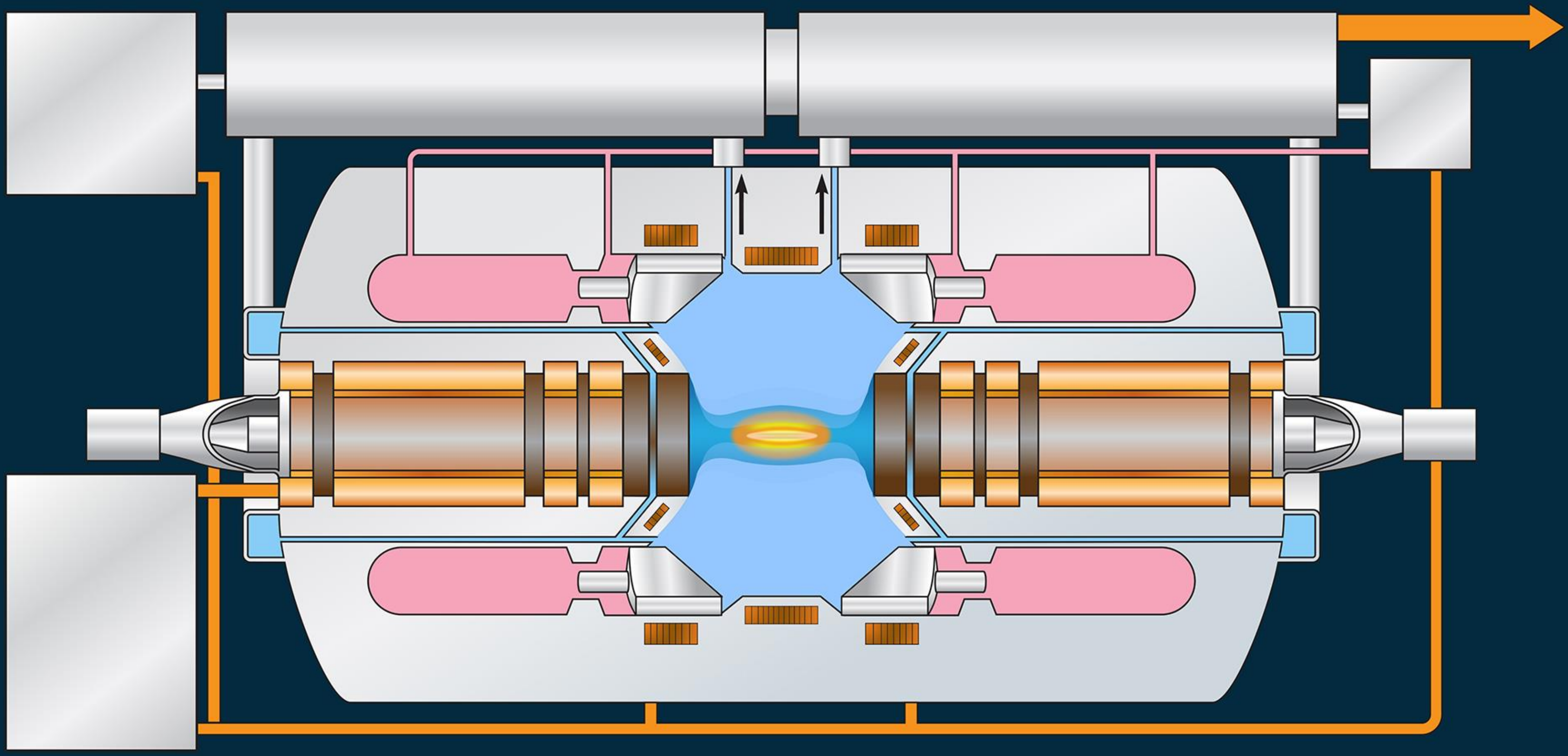
The Stabilized Liner Compressor (SLC) uses free-pistons, driven by high-pressure gas, to implode a hollow cylinder of rotating, liquid metal that surrounds magnetic flux and a plasma target.



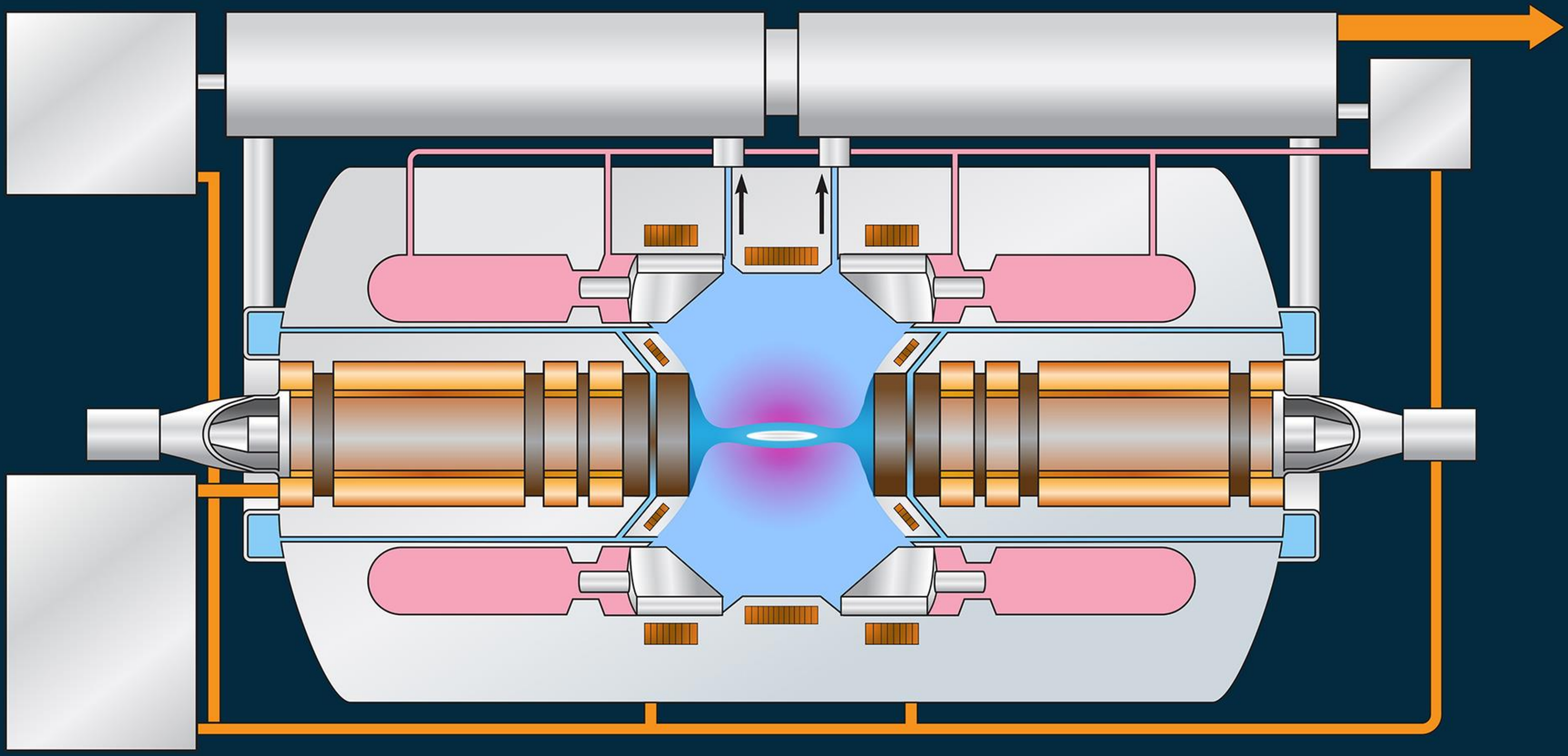
Rotation stabilizes Rayleigh-Taylor modes during the final compression of the plasma target, while the free-piston drive eliminates Rayleigh-Taylor instability during acceleration and re-capture of the liner material. These two mechanisms permit control of the high-energy density implosion and re-expansion and provide repetitive operation.



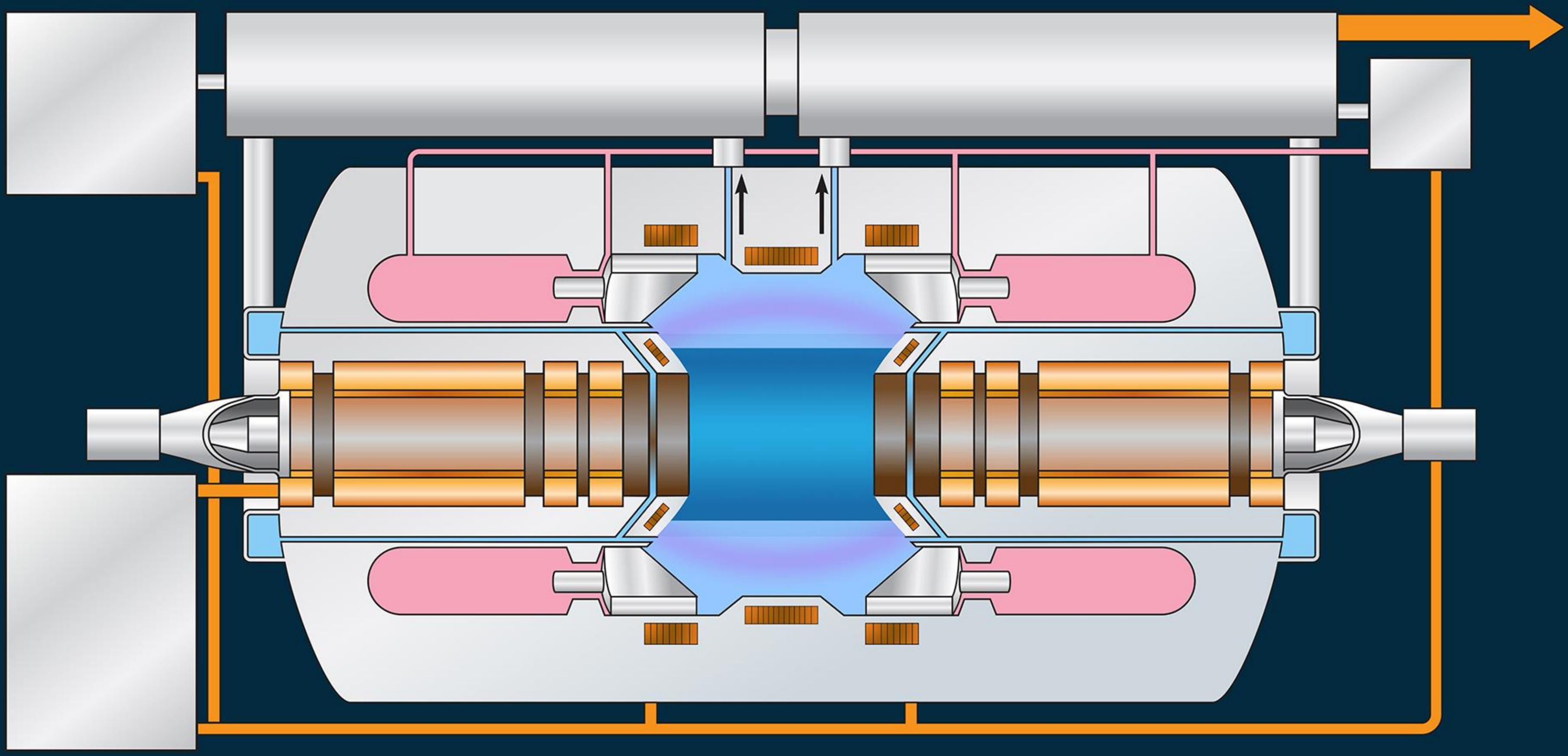
Injection of compact toroid magnetized-plasma



Strong adiabatic compression replaces costly beam- and RF-heating to achieve fusion temperatures.

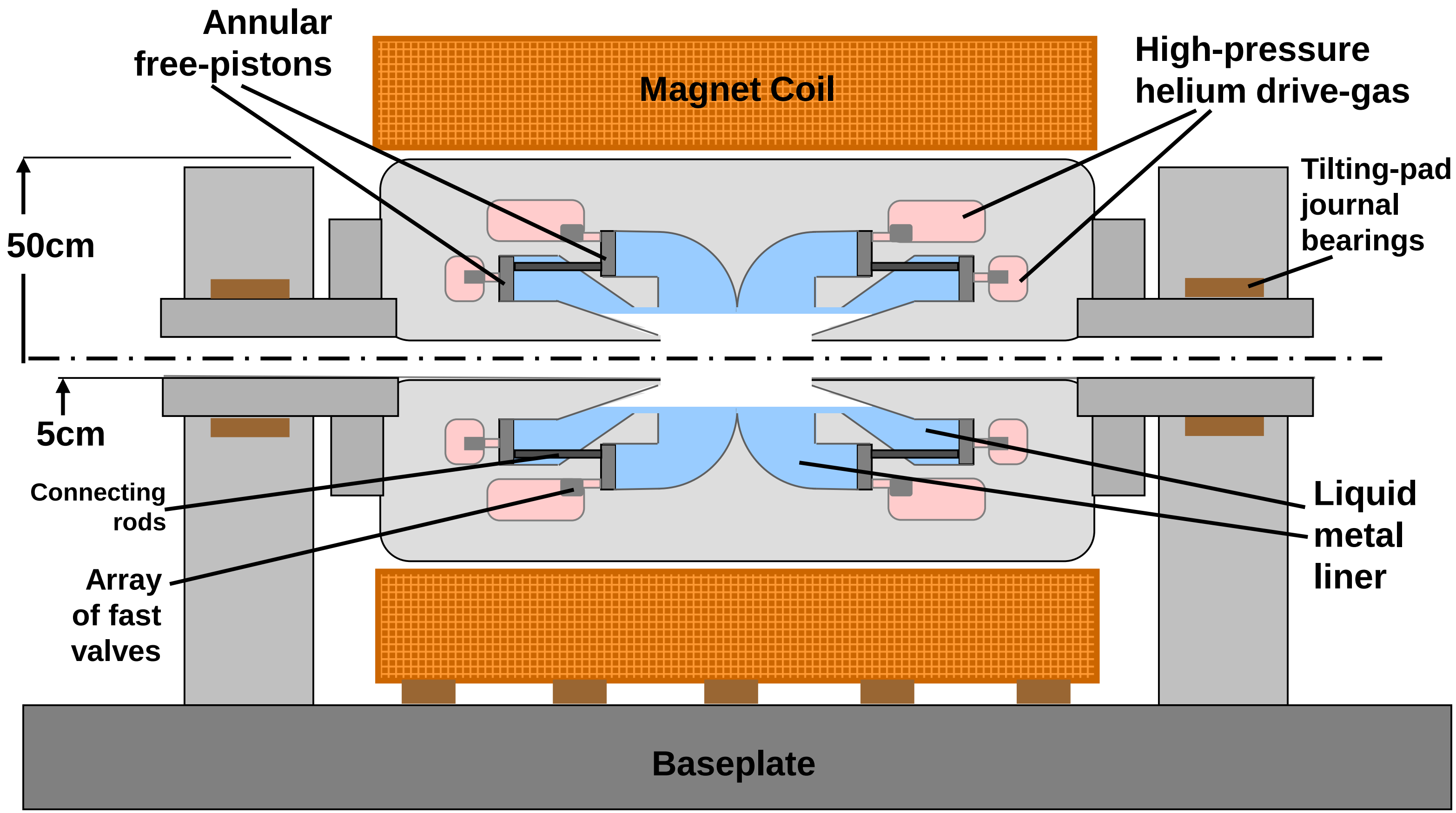


Liner serves as reactor blanket to protect electrical components from neutron damage.



Liquid liner provides medium for heat transfer and tritium recovery.

The basic arrangement for SLC resembles variants of the stabilized liner implosion system for Linus at the Naval Research Laboratory in using "ganged" free-pistons to allow for plasma targets of arbitrary length.



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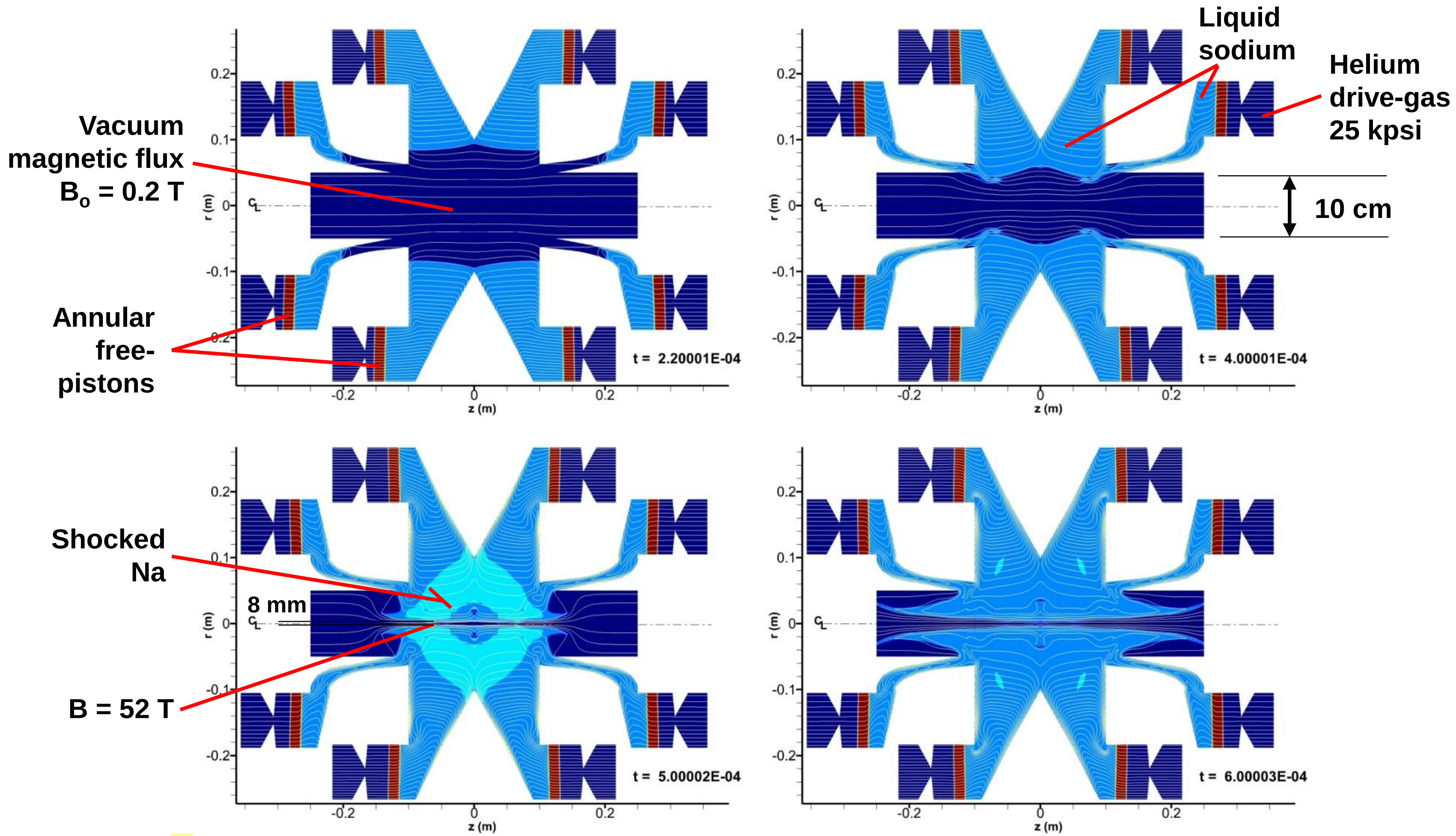
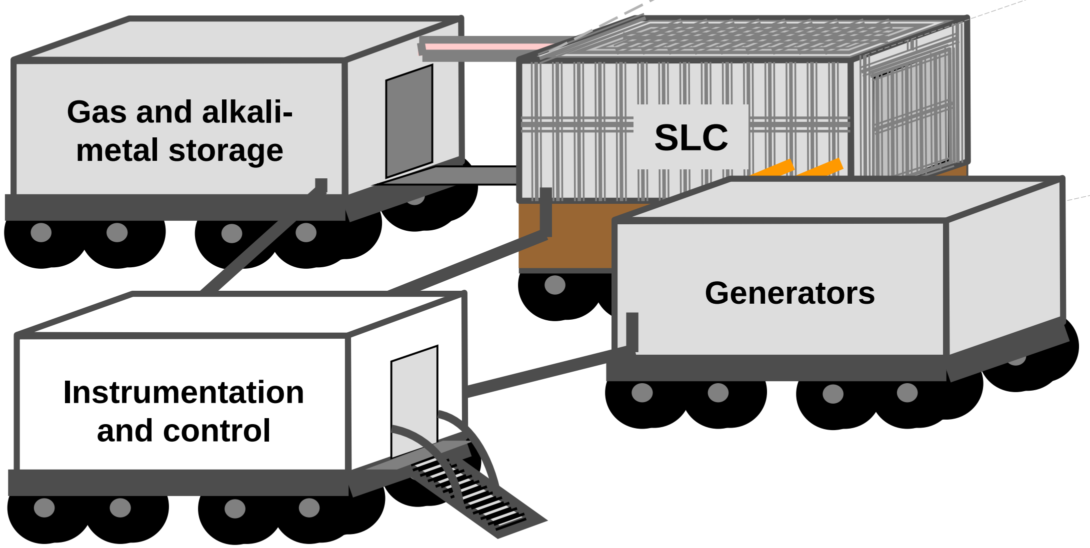
We are using the MACH2 code to simulate the unsteady, compressible behavior of the rotating liner in SLC.

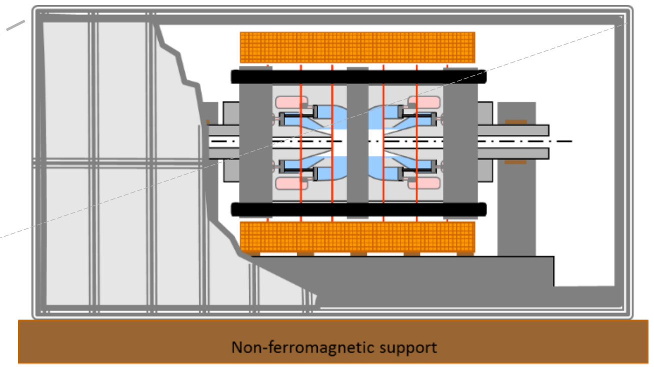
SLC in “ganged-piston” arrangement



MACH2 also provides pressure distributions <u>vs</u> time to guide structural design using SolidWorks.

Thanks to high energy-density of pneumatic energy storage and switching SLC is much smaller than the plasma target generator, so we must travel to the plasma.



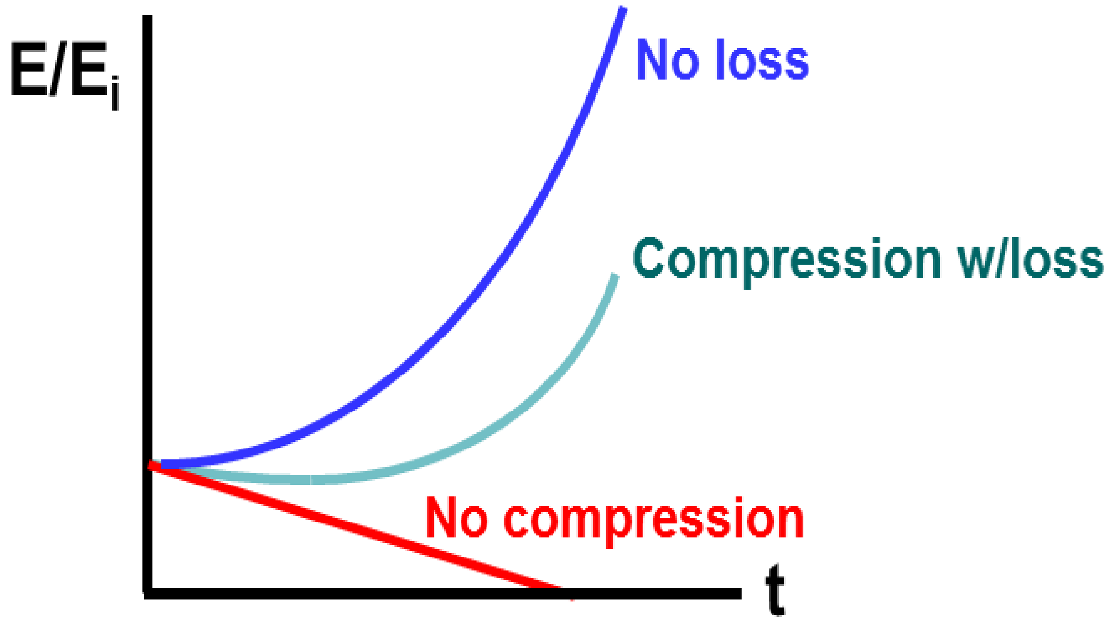


SLC Container protects against multiple hazards and latent defects

Transport and siting of the SLC system would involve four trailers for operation of SLC at a NumerEx location. For the plasma experiments, elements would shift to accommodate plasma laboratory requirements.

During compression, the temperature and magnetic field both increase, which could change the plasma lifetime from the static value. This requires more understanding of the plasma target behavior (which is why we would do the experiments).

If the loss rates are dominated by Bohm-like diffusion, we may solve analytically for the energy change, assuming a trajectory for the inner surface of the liner



For energy at r = 2X final radius, and total radial compression of 10:1, E/E_i = 13, if the implosion time equals the loss time; (20:1, gain is 39).

Goal of SLC: provide technology to enable plasma target development at high magnetic fields.

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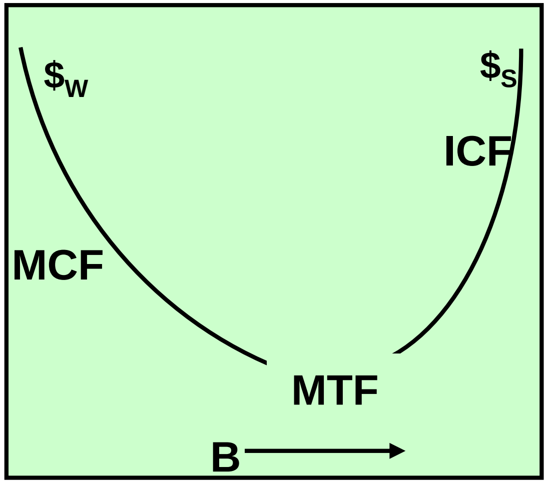
Backup Slides

STABILIZED LINER COMPRESSOR FOR LOW-COST CONTROLLED FUSION POWER



1. There's an optimum, lower-cost regime between the two mainline programs for controlled fusion.

2. To access this regime requires new technology based on non-explosively driven plasma target compression.

3. Such compression has generally been destructive in the laboratory because of various instabilities, which have prevented adequate progress.

4. The *Stabilized Liner Compressor* conquers these instabilities and permits repetitive compression for plasma development and for an economical fusion power reactor.

5. It does this by spinning a hollow cylinder of liquid metal and forcing it inward onto the plasma using a piston driven by high-pressure gas.

6. The liquid metal shields against the high-energy fusion neutrons, and automatically provides heat transfer and production of fusion fuel for the reactor.

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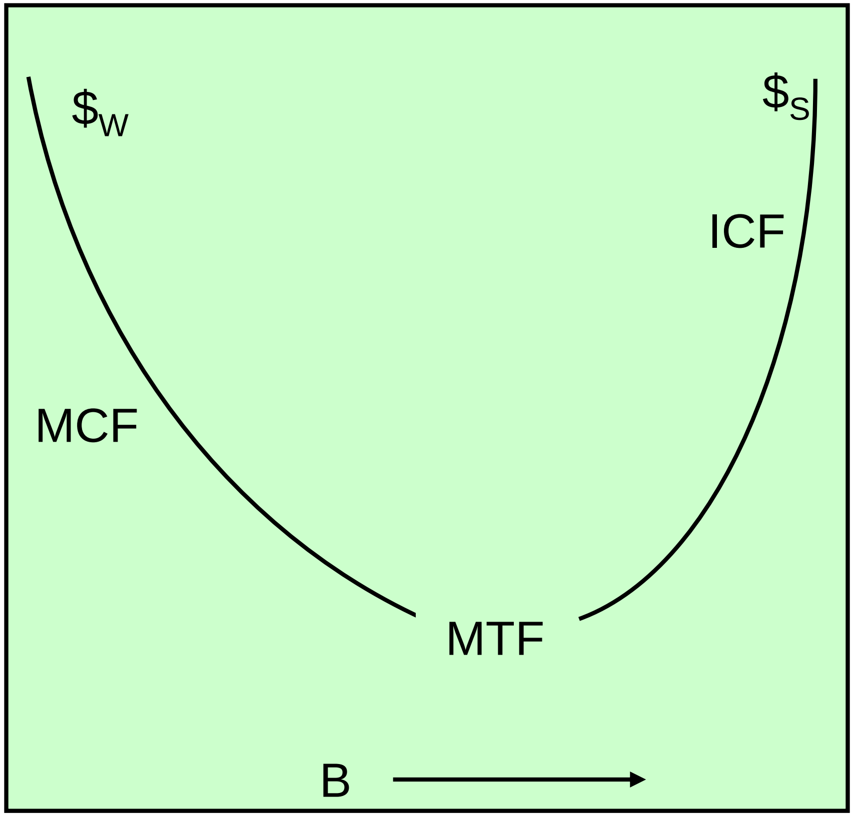
Magnetized Target Fusion (MTF) offers possible optimum between conventional magnetic- and inertial-confinement fusion regimes.



P.J. Turchi, *IEEE Trans. on Plasma Science*, 36, 1, 52 (2008).

Fusion energy gain: $Q \sim n\tau$

At a given plasma temperature $n \sim B^2$, $\tau \sim x^2/D$ and $D \sim 1/B^{1\div2}$, so needed energy for <u>magnetic-confinement fusion</u> (MCF), based on diffusion is

$$W_p \sim B^2 x^3$$

$$\sim Q^{3/2}/B^{2.5\div4}$$

For <u>inertial-confinement fusion</u> (ICF),

$$W_p \sim Q^3/B\rho^{3/2}$$

But power density is critical

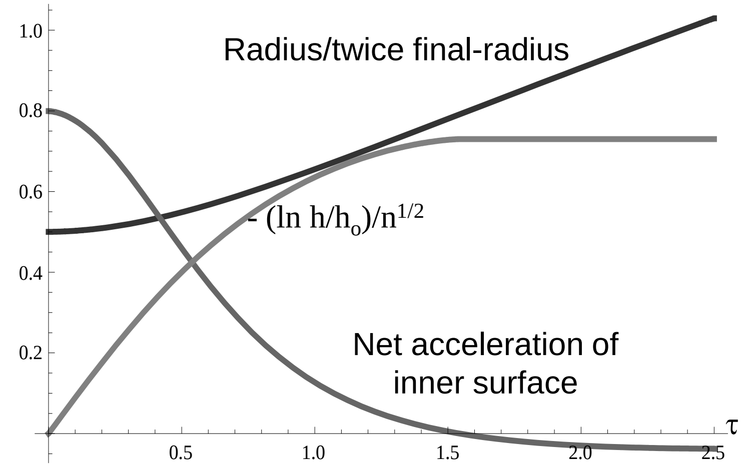
$$S \sim W_p/x^2\tau_p \sim Q^9/W_p^3\rho^5$$

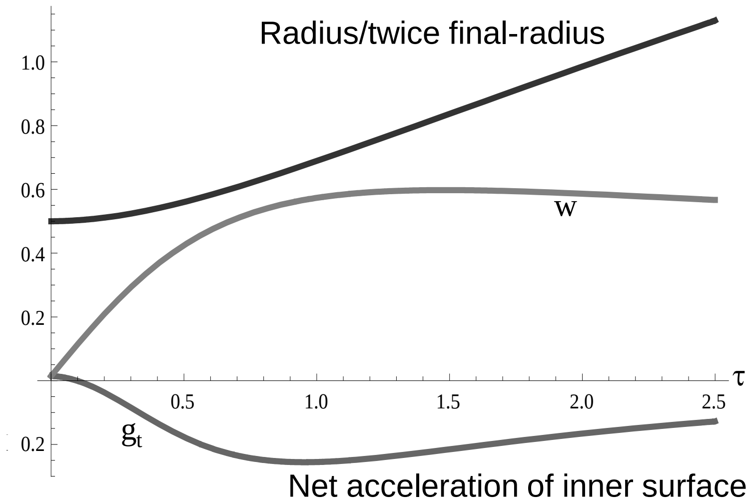
$$\sim B^3/\rho^{1/2}$$

System cost: $\$ = K_w W_p + K_S/W_p^3$

To achieve very high magnetic fields (~ megagauss-levels) requires dynamic conductors, known as imploding liners.

In the final few diameters of efficient compression of a plasma target by a liquid liner, the inner surface becomes Rayleigh-Taylor unstable.





P.J. Turchi, *IEEE Trans. on Plasma Science*, 43, 1, Part II, 369 (2015).

Allowable Initial Perturbation δ_o

(for cylindrical implosions with ε_b = 90%)

regime [μs]	minimum radius, r_o [cm]	δ_o [μm]
10	5	7.6
1	1	1.52
0.1	0.1	0.152

The above "budget" for perturbation amplitudes at the beginning of deceleration is applied after such initial perturbations have already grown earlier in the implosion.

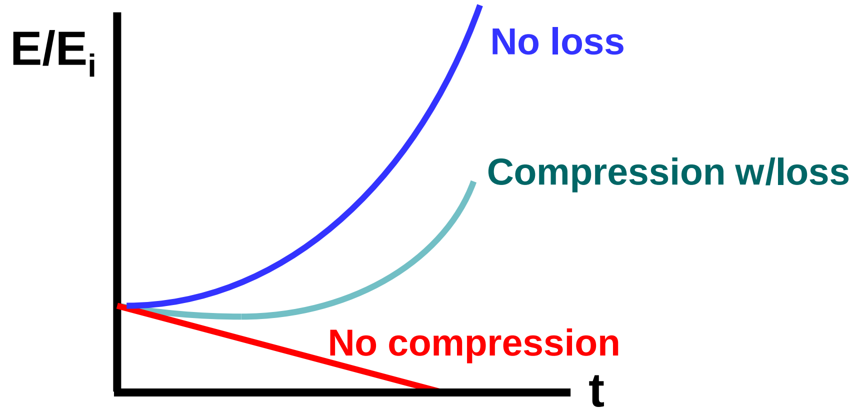
Sufficient rotation adds $-v^2/r$ that eliminates positive net acceleration and stabilizes all mode numbers n. With free-piston drive, this permits stable exchange of energy between target and pneumatic drive.

Analytic solution of liner compression of plasma for cylindrical implosion indicates optimistic result.

$$E/E_i = (r_i^2 - 2u_c r_c t) / 3.6 u_c r_c t_{ei} + (1 - r_i^2 / 3.6 u_c r_c t_{ei})[\, r_i^2 / (r_i^2 - 2u_c r_c t)]^{0.8}$$

where $u(t)r(t) = u_c r_c$ for a cylindrical implosion and subscript 'I' refers to conditions at initial plasma injection.

For energy at r = 2X final radius, and total radial compression of 10:1, E/E_i = 13, if the implosion time equals the loss time; (20:1, gain is 39).



With compression time ~ $r^2/ u_c r_c$, the energy may actually decrease during early portion of plasma compression until the rate of work 1.6 Eu/r exceeds the loss rate E_i/t_{ei}. The speed u_c is independent of size r_c. Search for 'X' depends on size and lifetime of potential plasma target.

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